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A NEW EXPLANATION OF THE BLAZHKO EFFECT IN RR LYRAE STARS

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ABSTRACT

An interpretation of the modulating Blazhko effect in RR Lyrae stars is presented here, in which turbulent convection inside the hydrogen and helium ionization zones becomes cyclically weakened and strengthened owing to the presence of a transient magnetic field that is generated in situ by either a turbulent or a rotational dynamo mechanism. Successful predictions, both qualitative and quantitative, are made for the small changes of the primary pulsation period, the fluctuations of light and velocity amplitudes, the slow periodicity and irregularity of the Blazhko cycles, the restricted ranges of effective temperature for the RRab and RRc Blazhko variables, and the complex correlations between the primary period change, amplitude change, and mean effective temperature. Characteristic features of the predicted light and velocity curves at high and low amplitudes, even though they are based on radiative stellar models, agree well with the observed features, for the most part. The present theory of the Blazhko effect is simple enough that it does not require any basic change in our current understanding of RRab and RRc stars as being purely fundamental-mode and first-overtone radial pulsators. It also accounts naturally for the observed fact that hotter and cooler classes of periodic variable stars do not exhibit the Blazhko effect.

Subject headings: stars: interiors — stars: magnetic fields — stars: oscillations — stars: variables: other — turbulence

1. INTRODUCTION

The Blazhko effect in RR Lyrae stars consists of a slow (days to months) cyclical modulation of the period, amplitude, and shape of the light and velocity curves (Blazhko 1907; Shapley 1916; Szeidl 1988; Smith 1995). The effect is seen in 10%–30% of RRab stars (Szeidl 1988; Alcock et al. 2003) and in roughly 2% of the RRc stars (Alcock et al. 2000); the RRab stars are thought to be fundamental-mode radial pulsators, while the RRc stars are considered to be first-overtone radial pulsators (Schwarzschild 1941; Christy 1966). When a period change occurs, it sometimes does so very rapidly; the amplitude then simultaneously follows suit. In a few stars, the period of the Blazhko cycle itself varies by a small percentage. In addition, much slower modulations of the light and velocity curves have been detected, with a less regular character. It is also known that the Blazhko effect can temporarily disappear in some stars. All of these changes, however, are far too fast to be accounted for by ordinary evolutionary effects (Lee 1991).

The observation of a small, but significant, irregularity in the Blazhko period makes it difficult to explain the whole phenomenon by invoking mechanisms that produce an essentially clockwork regularity, such as tides in a binary system (Fitch 1967), binary light-time effects (Jurcsik et al. 2002b), pairing of binary companions of RR types ab and c (Kinman & Carretta 1992), nonadiabatic splitting of a radial mode (Ledoux 1963), a 2:1 resonance between the fundamental radial mode (for RRab stars) and either the second overtone (Kluyver 1936; Walraven 1955; Borkowski 1980) or the third overtone (Borkowski 1980; Moskalik 1986; Goranskii 1989), a resonance between a radial mode and either an unobservable nonradial mode (Vandakurov 1967; Cox 1993; Kovács 1995) or an observable nonradial mode (Fahlman 1971; Cox 1993; Kovács 1995; Van Hoolst et al. 1998; Nowakowski & Dziembowski 2003; Dziembowski & Mizerski 2004), or the changing aspect of a magnetic oblique rotator-pulsator (Balazs-Detre 1959; Balazs-Detre & Detre 1962; Christy 1966; Cousens 1983; Shibahashi 2000).

Other objections have been raised against these proposed mechanisms. No convincing evidence of any binary motion or of a binary companion's light has ever been found, even in Kinman & Carretta's (1992) best case of AR Her (Smith et al. 1999). Theoretical models of stellar pulsation do not reveal split radial modes, and, except in extremely rare instances, do not yield either a direct or a resonant excitation of the second (let alone the third) overtone. Borkowski (1980) himself acknowledged this drawback, and also pointed out the narrow range of conditions for a 2:1 radial resonance, including the need for unreasonable stellar masses. The mechanism also does not explain long-term changes in the Blazhko effect or the existence of non-Blazhko stars with the same primary pulsation periods (Smith 1981). Finally, a small percentage of RRc stars are Blazhko variables (Alcock et al. 2000); being first-overtone pulsators, they would accordingly require the excitation of some even higher order mode than the third overtone.

If a resonance between the fundamental radial mode and a nonradial mode occurs, energy transfer from the radial to the nonradial mode would be needed (Vandakurov 1967; Nowakowski & Dziembowski 2003); however, the predicted nonradial amplitude appears to be too small, and some Blazhko variables would have to show comparable radial and nonradial amplitudes for this interpretation to hold (Dziembowski & Mizerski 2004). Moreover, it would be necessary that the nonradial mode influence the light curve only in the neighborhood of maximum light, so as to leave the rest of the light curve essentially unchanged, as observations require (Detre 1956).

The fact that the variable V79 in M3 had apparently been a Blazhko RRab that later changed into a double-mode RRd has suggested mode mixing as a Blazhko mechanism (Clement et al. 1997; Clementini et al. 2004); however, if the apparent Blazhko RRab had been all the time a RRd with a very low first-overtone light amplitude (<0.25 mag), the observations might be equally well accounted for. More study of this star is required.

The magnetic oblique rotator-pulsator model runs into the serious problem that magnetic fields in these stars have never been observed except in RR Lyr itself, while even those observations are questionable (see below). Earlier objections (Kovács 1995) to rather naive predictions about the light amplitude modulation have been met by the more sophisticated models of Shibahashi (2000); however, Blazhko stars exhibit more complicated changes in the light curve (as well as small period irregularities) that the model cannot yet explain (Alcock et al. 2000).

All proposed models that rely on nonradial effects require axial rotation of the stellar envelope, whose period is then identified with the observed Blazhko period. However, angular momentum considerations make it difficult to explain the nontrivial changes of the Blazhko period by up to 1%–2% in some stars (Smith et al. 1999; LaCluyzé et al. 2004). Moreover, measurements of line widths in RR Lyrae stars, including stars with very short Blazhko periods, show no observable surface rotation that is fast enough to be relevant, although this conclusion is still tentative (Peterson et al. 1996; Jurcsik et al. 2005a).

Several proposals have been offered to explain at least the observation of a small, rapid change of the primary pulsation period, even if, by themselves, they cannot explain the whole Blazhko effect. Burbidge (1956) considered the effect of a magnetic field on the period, but he was interested only in the fixed offset of the period and wrongly got a large effect from the deeper layers of the envelope. This flaw was later corrected, in an independent analysis, by supposing a buoyant rise and subsequent decay of magnetic flux tubes coming from the radiative interior into the convective near-surface layers of the envelope, where the pulsation amplitude is largest (Stothers 1980). However, the required interior magnetic field is uncomfortably large. Steady mass loss from the stellar surface might likewise produce both positive and negative period changes (Laskarides 1974; Koopmann et al. 1994), but these changes are unlikely to be rapid enough to explain the observations. Semiconvective mixing events in the stellar core comprise another possibility (Sweigart & Renzini 1979), as does the dredge-up of helium, gravitationally settled beneath the outer convection zone, by sporadic convective overshooting events (Cox 1998); however, a sufficient regularity in these convective mixing events to account for the Blazhko effect is not easily obtained.

Since convective overturning times in the outer envelope are only of the order of hours to a day, mechanisms for changes of the pulsation period that involve convection may well be favored. Because the source of pulsational driving lies in that part of the convection zone where hydrogen and helium are undergoing ionization, disturbances of the structure of this region should affect the amount of pulsational driving and hence the observable surface amplitudes. Creation of a magnetic field by dynamo action in the convection zone and its subsequent destruction by ohmic decay and by convective twisting and shredding of the field lines seems like a reasonable possibility, because such magnetic phenomena are believed to occur in the convective envelope of the Sun. Strong magnetic fields can theoretically then act back on and brake turbulent convection in more weakly convective stellar environments like RR Lyrae envelopes. Hydrostatic and thermal adjustment timescales in this case are expected to be very short, as turbulent convective transport and radiative diffusion through the outer layers occur in a matter of hours—which is very similar to the pulsation period.

In the present paper, we test a novel proposal that the changes in pulsation period and amplitude of RR Lyrae stars are due simply to changes in the overall strength of the envelope convection. The length of the pulsation period is thus predicted to show a (possibly complicated) correlation with the magnitude of the pulsation amplitude. Our tests of this proposal are performed by using theoretical stellar envelope models and published observations of RR Lyrae stars. Although most of the present ideas and even the needed model calculations were generated 25 years ago, we have decided to publish them now since no current explanation of the Blazhko effect has proven to be fully satisfactory.

2. STELLAR MODELS

The nonlinear stellar models used here are those that we derived earlier for RR Lyrae stars of Bailey types a and b (Stothers 1981). Our standard model was constructed with the following parameters: mass $M/M_\odot = 0.578$, luminosity $\log(L/L_\odot) = 1.585$, effective temperature $\log T_e = 3.813$, helium abundance $Y = 0.25$, and metals abundance $Z = 0.005$. Uncertainties in the chemical composition and opacities are relatively unimportant for RR Lyrae stars, and so variations were made primarily in the other three parameters by choosing $M/M_\odot = 0.679$, $\log(L/L_\odot) = 1.800$, and $\log T_e = 3.792$. The fundamental mode of radial pulsation was computed for moderately deep, radiative stellar envelopes, starting from a nonstatic configuration with very low velocity amplitude (typically $\Delta V \approx 20$ km s^{-1} at the surface). The structure was then integrated forward in time, using occasional small artificial boosts of the velocity amplitudes, until the fundamental limit cycle was attained.

Reexamination of our nonlinear models shows that all of them display, rather consistently, a very small period increase between the states of low and high surface velocity amplitude. From $\Delta V \approx$ 40 to 80 km s^{-1}, the growth amounts to $\delta P/P \approx +0.002$. If the 1980 Los Alamos opacities are substituted for the 1980 Carson opacities in our standard model, the result for the period growth is unchanged. Christy (1966) had already looked for period changes in his radiative models, but did not find any at a level of 10^{-3}. Bono & Stellingwerf (1994), on the other hand, found slight period *decreases* of $\delta P/P \approx -0.004$ between their linear and their full-amplitude nonlinear radiative models. These differing results suggest that any physical period change must lie close to the noise level and that a limit can be set at $|\delta P/P| \leq 0.002$, which is associated with the rise from moderately low to high amplitudes.

To assess the effect on the pulsation period of the main neglected feature, convection, which transports material between the surface and the bottom of the second helium ionization zone, we adopt convective mixing-length theory and linear nonadiabatic pulsation theory, and consider changes of the ratio, α, of the convective mixing length to the local pressure scale height. At fixed stellar radius, an increase of α above its value 0 in the purely radiative case alters the model's structure slightly, raising the value of P. On the other hand, knowing that the very deep radiative layers must remain unaffected by the near-surface convection (Schwarzschild 1958), it is also necessary to determine the actual amount of decrease of surface radius that leaves the inner structure unchanged for any specified increase of α. This decrease of radius then lowers P. Combining these two effects, which have opposite signs, allows us to find the small net change of P. For our standard model with first $\alpha = 0$ and then $\alpha = 2$, we obtain $\delta P/P = +0.001$. For the higher luminosity model, $\delta P/P = +0.004$. When the effective temperature is reduced or the stellar mass is increased, $\delta P/P$ drops to negative values as low as -0.02, because convection in these two cases becomes much more efficient. A comparison of a radiative full-amplitude nonlinear model and a similar convective model, constructed with $M/M_\odot = 0.578$, $\log(L/L_\odot) = 1.813$, and $T_e = 3.771$ by Gehmeyr (1992), yields $\delta P/P = -0.02$, in agreement with our linear results for cool models. A similar comparison of radiative and convective nonlinear models by Bono & Stellingwerf (1994) for $M/M_\odot = 0.650$ and $\log(L/L_\odot) = 1.810$ gives $\delta P/P = +0.003$ ($\log T_e = 3.826$) and

$\delta P/P = -0.007$ ($\log T_e = 3.778$), again in qualitative agreement with our results. This exercise, admittedly, can demonstrate only the approximate size of the expected changes of period if convection were to become cyclically quenched and then reconstituted over some time interval that is long compared to the local timescales for turbulent convective overturn or for radiative diffusion.

Although the mathematical treatment of convection and its interaction with radial pulsation is still in a rather primitive state, a number of numerical studies of convective RR Lyrae models have concluded that convection significantly reduces the pulsational amplitudes (Deupree 1977; Stellingwerf 1984; Gehmeyr 1992; Feuchtinger 1999). This reduction occurs even though, paradoxically, pulsation tends to weaken convection, as Christy (1964) first recognized. Are there any other factors that might influence convection? Strong enough magnetic fields might quench convection. Suppose that the turbulent dynamo mechanism (Batchelor 1950; Vainshtein & Cattaneo 1992; Thelen & Cattaneo 2000; Lee et al. 2003) builds up a magnetic field inside the hydrogen and helium ionization zones. The magnetic flux tubes, being buoyant, migrate upward. If the magnetic energy grows to near equipartition with the turbulent energy, convection might be partly choked off. The magnetic field then weakens through ohmic decay and continued convective shredding of the field lines. Convection eventually resumes vigorously, and the dynamo process then repeats itself. Since the total turbulent energy is very small compared to the gravitational potential energy of the pulsating layers in an RR Lyrae envelope, the direct effect of any dynamo-built magnetic field on the pulsation period would be negligible (Stothers 1980). The main effect of the field on the period would come through the reduction, or suppression, of convection. The whole process being in part stochastic, each magnetic cycle need not occur with exactly the same period and same strength as the previous cycle. Since the turbulent dynamo mechanism does not require either a seed magnetic field or axial rotation of the star to build up the field, a slow periodicity in the magnetic variations could result from the necessity of a certain number of convective overturning times or of pulsationally controlled local convective start-and-stop cycles to attain the maximum field strength. The associated slow periodic variation of the overall turbulence field should be carefully distinguished from the ordinary short-period amplification and dissipation of turbulent convection that occurs during the primary pulsation cycle itself. But it may well be that the more rapid interaction between pulsation and convection constitutes the pump for the much slower turbulent dynamo that generates the magnetic field.

If the star is rotating, centrifugal force might also be involved, as in the case of the Sun. Overshooting turbulent convection in the Sun probably pumps magnetic flux down into the immediately underlying stable radiative layers by the action of downflowing convective plumes (Tobias et al. 2001). The relatively stable stratification of these "tachocline" layers can then prevent the magnetic flux tubes from rapidly rising; hence a large reservoir of magnetic field can be built up. Local torsional oscillations set up by the star's rotation would then periodically release some of the stored magnetic flux upward (Layzer et al. 1979). The connection between the rotational period and the magnetic period need not be very close, because at least in the case of Sun these two periods differ by a factor of ~ 300. A rotational dynamo mechanism for RR Lyrae stars, however, seems more contrived than a simple turbulent dynamo mechanism.

In a time-series spectral analysis of the surface light or surface velocity curve of an RR Lyrae star, what would one expect to see? A purely sinusoidal amplitude modulation of a single radial oscillation mode would produce a symmetric triplet of frequencies,

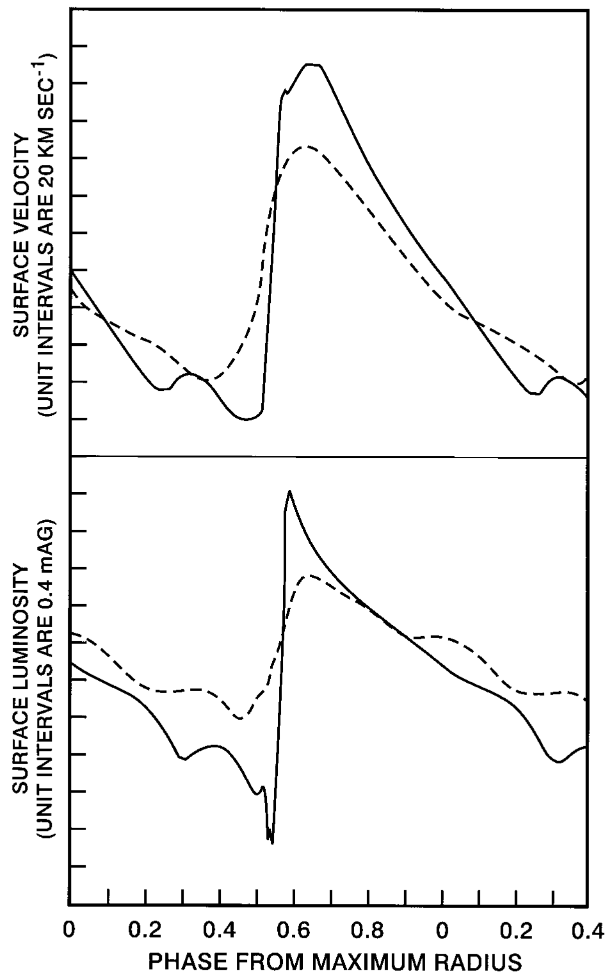

FIG. 1.—Surface velocity curve and surface luminosity curve for an RR Lyrae model with a period of 0.536 days, pulsating at full amplitude (*solid lines*) and at roughly half of full amplitude (*dashed lines*).

spaced by the modulation frequency (Smith et al 1994; Jurcsik et al. 2005a). Of course, any amplitude and period irregularities as well as any noise in the data would perturb this simple triplet structure. Accordingly, we note that although triplets are observed for many Blazhko RR Lyrae stars, other types of multiplets and spacings are also observed in some cases (e.g., Alcock et al. 2000, 2003). These might well be only "ghost" modes. It is important here to recognize that the occurrence of multiplets does not necessarily imply the presence of more than a single oscillation mode.

The influence of pulsation amplitude on the general shapes of the predicted surface light and velocity curves can be seen in Figure 1 for a nonlinear radiative stellar model with an exceptionally high amplitude and for the same model at roughly half that amplitude. The full-amplitude light and velocity curves shown here are representative of a grid of curves that compare well in at least their overall shapes with observations of RRab stars, although not all details can be trusted (Stothers 1981; Simon 1985; Petersen 1985). They, as well as the half-amplitude light and velocity curves, will be discussed further below.

3. COMPARISON WITH THE STAR RR LYR

For a critical comparison with our theoretical predictions, we have analyzed the long series of accurate, closely spaced photoelectric observations of RR Lyr that were published by Walraven

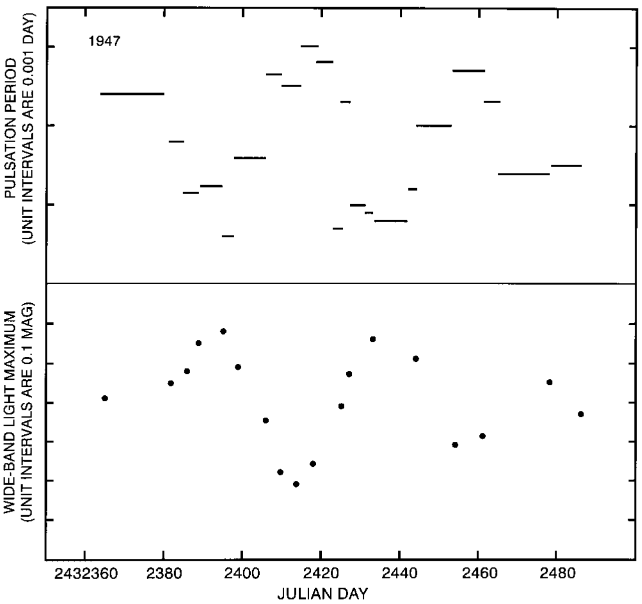

FIG. 2.—Pulsation period and wide-band photoelectric light curve maximum observed for RR Lyr during 1947. Data from Walraven (1949).

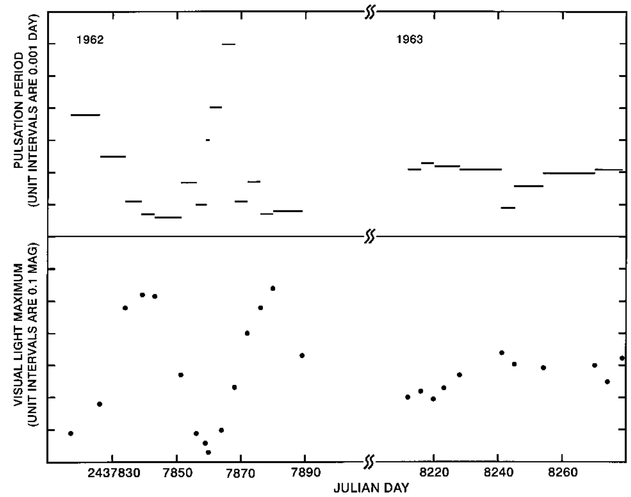

FIG. 3.—Pulsation period and visual light curve maximum observed for RR Lyr during 1962 and 1963. Data from Preston et al. (1965).

(1949) and Preston et al. (1965). Over suitably short observing intervals, dictated by the availability of the data, a mean pulsation period can be formed for each interval, using the time of median light on the rising branch as a zero point for the phase; in the present applications, the number of pulsational cycles per interval ranges from 2 to 30, but is usually at least 7. Light maximum was not always observed, although its phase could usually be determined; therefore, the data for the measured magnitude at maximum are sparser than those for the calculated pulsation period. Results are plotted as a function of Julian day for the years 1947 and 1962–1963 in Figures 2 and 3, respectively. Similar results are obtained if the zero point for the phase is taken to be the time of light maximum or of light minimum.

The first feature to be noted is the cyclic rise and fall of the pulsation period and of the light amplitude. This constitutes the Blazhko effect; in RR Lyr its period is 41 days. The different Blazhko cycles, however, are seen to vary greatly in their amplitudes and, to a much lesser extent, in their durations.

Second, the pulsation period is seen to be exactly (insofar as the observations allow) anticorrelated with the light amplitude. Since RR Lyr shows a mean period $P = 0.567$ days and a mean visual amplitude $\Delta M_{\rm vis} = 1.0$, the small change of $\delta P/P = +0.004$ in 1947 when the amplitude dropped by nearly a half is consistent with our hot theoretical models undergoing convective quenching. In fact, RR Lyr is a typically hot member of its class, having an average $\log T_e = 3.813$ (Oke & Bonsack 1960; Searle & Oke 1962; Preston et al. 1965). During the two additional Blazhko cycles in 1962 and 1963, $\delta P/P$ rose to +0.009 and fell to +0.002, at times when the light amplitude change was greater than and smaller than usual, confirming the trend of the predicted variability of $\delta P/P$.

Third, although the Blazhko effect nearly disappeared in 1963, the star's pulsation amplitude at that time was intermediate between high and low states. According to our theory, convection must have then held steady with reduced vigor. For RR Lyr as well as other Blazhko variables, the largest pulsation amplitudes are observed to be nearly equal to the pulsation amplitudes of non-Blazhko variables with the same periods (Preston 1964; Szeidl 1988; Piersimoni et al. 2002). Since this condition would be expected to correspond to the most severe quenching of convection, the question arises as to why so many non-Blazhko variables occur in this extreme state. Possibly the explanation is that a very high pulsation amplitude is likely to inhibit vigorous convection, irrespective of a magnetic field, as Christy (1964) has suggested and as nonlinear convective models continue to permit (Feuchtinger 1999). Thus the Blazhko variables would be stars with mean amplitudes low enough to facilitate vigorous convection, with the consequence that magnetic fields get built up that can then modulate the convection. How a Blazhko variable would get out of its high-amplitude state remains a problem, but such a star would differ from a non-Blazhko variable by possessing a significant magnetic field, which would then be able to decay, allowing convection to restart. Jurcsik et al. (2002a) have shown that the Fourier components of the light curves of Blazhko variables pulsating at full amplitude do not quite match those of non-Blazhko variables with the same periods.

Walraven (1949) has published two excellent wide-band photoelectric light curves during high-amplitude and low-amplitude phases of the Blazhko cycle of RR Lyr. At high amplitude, the skewness of the light curve increases, the peak is affected more than the descending branch, and the small secondary bump that appears shortly before light minimum is enhanced. These three features agree well with our models shown in Figure 1. Since the observed velocity curves follow the light curves in both amplitude and phase (Struve & Blaauw 1948; Preston et al. 1965), they do not need any special discussion here. The modulation of the light and velocity curves in both RR Lyr and the other Blazhko variables is centered around the time of median light on the rising branch (Struve & Blaauw 1948; Hardie 1955; Preston et al. 1965; Romanov 1977; Gillet & Crowe 1988; Jurcsik et al. 2005b). The higher the pulsation amplitude, the stronger is an atmosphere shock disturbance at this time; the shock gives rise to both hydrogen emission and an ultraviolet excess that makes the star appear bluer. In our high-amplitude model, the associated perturbation in surface velocity appears as a small blip just before the outward velocity maximum. At lower amplitude, Preston et al. (1965) found a prominent stillstand on the rising branch of the observed light curve. This feature appears only marginally in our low-amplitude model's light curve. In general, our models in the neighborhood of minimum light have not been calculated with very high accuracy.

In addition to the fundamental pulsation period of 0.567 days and the Blazhko period of 41 days (Shapley 1916; Walraven 1949), RR Lyr shows a number of longer periods of questionable length and stability: 122 days (Walraven 1949), 4 yr (Detre & Szeidl 1973), and 10–16 yr (Shapley 1916; Detre 1956; Fringant 1961). If these longer periods eventually turn out to be real, they may resemble, and may have an origin similar to, the long periods of activity observed in the Sun, i.e., 11 (or 22), ~80, and ~200 yr. Therefore, they may likewise arise from complex dynamical interactions between convection, magnetic fields, and, at least for the Sun, rotation. Several other Blazhko variables are known to exhibit such long periods (LaCluyzé et al. 2004).

Whether or not RR Lyr possesses an observable magnetic field is a disputed question. This star has been reported as showing a magnetic field that was essentially absent in 1950, strong in 1955, and weak in 1956 (Babcock 1956, 1958); absent in 1963–1964 (Preston 1967); strong in 1978 and 1982–1984 (Romanov et al. 1987, 1994); and absent in 1999–2002 (Chadid et al. 2004). To explain this apparent variability, the field strength has been postulated to be varying in phase with the 0.567 day period (Romanov et al. 1987), the 41 day period (Balazs-Detre 1959; Detre 1962; Balazs-Detre & Detre 1962; Romanov et al. 1987), and the 4 yr period (Detre & Szeidl 1973). However, the finding of no magnetic field over 4 years by Chadid et al. (2004), together with their critical remarks about the significant measurement errors occurring in earlier work, suggests that RR Lyr possesses either no strong magnetic field or else a magnetic field that is buried deeply and is relatively weak at the surface (as apparently is the case for the Sun).

4. DISCUSSION

The Blazhko effect is explained here as the direct consequence of a gradual strengthening and weakening of turbulent convection in the stellar envelope. The predicted small changes of the envelope structure modify slightly the pulsation period, in agreement with observed changes in the prototype star RR Lyr. Strengthening of convection is expected to lower the pulsation amplitude, and if the reduction of amplitude can be mimicked by radiative stellar models that are part-way on their rise from zero to full amplitude, the agreement of the predicted light and velocity curves with those observed may not be fortuitous. In any case, at full pulsation amplitude, convection probably weakens greatly. Another factor that could weaken convection is a magnetic field, which can be slowly built up by the turbulent or rotational dynamo mechanism. Subsequent decay of this field leads to a slow cycle of varying turbulent convection, which can be identified with the Blazhko cycle.

Two points about this new model need to be emphasized. First, the model does not depend on any dredge-up of a large amount of magnetic flux from deeper layers in the interior, which would increase the total energy of the outer envelope and thereby change the pulsation period (Stothers 1980). In fact, the slight amount of magnetic flux that is either dredged up or created in situ by the dynamo mechanism would not be expected ever to exceed the turbulent energy, which is very small in RR Lyrae envelopes. Second, the observed change of pulsation amplitude does not come about from continual changes of the observer's aspect angle, as in the various models that rely on the excitation of nonradial oscillations—specifically, some beat-period models and the magnetic oblique rotator-pulsator model. Simple classical radial pulsation in a single mode—the fundamental mode for RRab stars and the first overtone for RRc stars—is sufficient.

In addition to the satisfactory agreement achieved with observational data for RR Lyr itself, the present theory can explain a number of other observed features of Blazhko variables, considered more generally. The observed irregularity of the Blazhko period arises here from the partial stochasticity of the proposed modulating mechanism, which also can account for the fact that no combination of short and long periods has ever been able to accurately reproduce the complex observed light curves (Detre 1962; LaCluyzé et al. 2004; Jurcsik et al. 2005b). The present theory also predicts no direct dependence of the Blazhko effect on metallicity, but this particular agreement with observations, namely that Blazhko variables are found at all metallicities (Smolec 2005), proves very little, because helium abundance, rotation rate, and magnetic field strength will also alter to some extent the incidence and period distribution of these variables.

Several statistical aspects of the RR Lyrae stars now also find at least a qualitative explanation. Previous theories have had a problem explaining the small number of RRc relative to RRab Blazhko variables among all RR Lyrae stars. In our theory, the hotter RR Lyrae stars—the type c—have less convection to begin with, and so would become modulated much less by a magnetic field. The hottest ones might not be modulated at all, and this would explain why the Blazhko effect in RRc stars occurs only among the cooler objects with longer pulsation periods (Smith 1981; Nemec 1985). Similarly, the coolest RRab stars are the most highly convective, to the extent that convection probably manages to quench pulsation at the red edge of the instability strip (Deupree 1977; Bono & Stellingwerf 1994). In such highly convective stars, magnetic fields would be relatively ineffectual in controlling the convection; this might explain the absence of any observed Blazhko effect in RRab stars with the longest pulsation periods (Preston 1964; Smith 1981; Nemec 1985; Gloria 1990). By extension, the highly periodic Cepheid variables, which are cooler still, would not be expected to show the Blazhko effect, and they do not. There may be here an analogy with ordinary main-sequence stars: the most visibly magnetic of these stars occur only among those stars containing small, transitional envelope convection zones.

Finally, our theory makes two more predictions, which still need verification. First, the pulsation period should vary either in phase or in antiphase with the pulsation amplitude during the Blazhko cycle. It is known to do so for RR Lyr itself—but how about other stars? Second, the change in pulsation period, $\delta P/P$, should shift its sign between the RR Lyrae stars with hot and cool effective temperatures. For the hot stars, $\delta P/P$ should be positive (in antiphase with the light amplitude), while for the cool stars, it should be negative (in phase with the light amplitude); the crossover effective temperature, at which $\delta P/P = 0$, is predicted to be 6400 ± 100 K in the case of fundamental-mode pulsators. Tsesevich (1969) has pointed out one anomalous Blazhko variable with large periodic variations in its light amplitude (and also in its radial-velocity amplitude [Romanov 1977]) but with precisely $\delta P/P = 0$: RZ Lyr. The effective temperature of this very metal-poor star is unknown, but its period (0.511 days) is fairly close to that of the less metal-poor RR Lyr (0.567 days), and its mean spectral type from the hydrogen lines is identical (Preston 1959). Since the effective temperature of RR Lyr itself (6500 K) lies near the predicted crossover effective temperature, RZ Lyr could well fall right on the mark. A similar star, MACHO 82.8410.55, has an almost identical period, 0.515 days (Kurtz et al. 2000).

Does the present model disagree in any significant way with the major observed features of the Blazhko effect? It does so in one important respect. As Figure 1 shows, the theoretical light curve when the star is pulsating at roughly half of full amplitude displays a minimum that lies well above the minimum value when the star is at full amplitude. In observed Blazhko variables, the minimum at half amplitude appears to be either just very slightly elevated or not at all; only the neighborhood of maximum light appears to be noticeably influenced by the reduction of the amplitude. This theoretical problem, however, does not affect the predicted velocity curves, which have been more accurately calculated than the light curves and agree much better, in this respect, with the observed radial-velocity curves; the maxima and minima of the observed radial-velocity curves are nearly symmetrical about the value of the star's mean radial velocity during all phases of the Blazhko cycle (Preston et al. 1965; Romanov 1977). Consequently, the light curve problem does not, at the moment, constitute a fatal blow to the theoretical models. An improved calculation of radiative and convective transfer in the outer layers and an application of the bolometric correction may be all that is needed.

It is also not possible at the present time to predict in a precise way the period of the Blazhko cycle. In the Sun, the dominant dynamical factor determining the period of the magnetic cycle is believed to be the period of axial rotation. If the ratio of solar magnetic period to solar rotational period provides an order-of-magnitude estimate of the time ratio needed for dynamo action to produce a magnetic cycle in a thin convective stellar envelope, then even though the dynamo for an RR Lyrae star would more likely be caused by pulsationally pumped turbulence than by rotationally controlled turbulence, the observed pulsation period of a half-day leads us to expect a possible magnetic period of $\sim$100 days. This is comparable, in general order of magnitude, with the observed Blazhko periods of 5–500 days (Smith 1995; Jurcsik et al. 2005a). Statistically, then, we might also predict that RRab and RRc stars with short pulsation periods should show smaller Blazhko periods, on the average, than stars with long pulsation periods, irrespective of their Bailey types. It long appeared that, observationally, there was no such correlation (Szeidl 1988; Smith 1995), but recently an enlarged data set has uncovered this very trend (Jurcsik et al. 2005a).

Although many of the ideas presented in this paper remain rather rough, some of them at least are quantitative, and all, taken together, appear to point to a plausible and economical explanation of the full Blazhko phenomenon.

The referee, Giuseppe Bono, has kindly pointed out two useful references, and has emphasized the importance of different past evolutionary histories for the structure of RR Lyrae envelopes.

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